Femoral osteochondroplasty can be performed effectively without the risk of avascular necrosis or femoral neck fractures in an experimental ovine FAI model

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Abstract: OBJECTIVE: The experimental induction of cam-type femoroacetabular impingement (FAI) in sheep is established. To tap the full potential of this ovine model, one should be able to perform a femoral osteochondroplasty safely. This study was based on previous cadaver experiments on the blood supply to the ovine femoral head and on the biomechanical strength of the proximal femur following offset creation. We hypothesized that offset creation in this ovine FAI model does not lead to (1) avascular necrosis (AVN) of the ovine femoral head or (2) iatrogenic femoral neck fractures and (3) can be performed effectively. DESIGN: In this experimental, controlled, prospective study nine sheep underwent unilateral FAI induction through an intertrochanteric, varus osteotomy. Seventy days following FAI induction, femoral osteochondroplasty was performed. Sheep were sacrificed after another 140 days. Radiographs, computed tomography (CT) scans and MRI were acquired. Histologic samples were stained with hematoxylin-eosin. (1) The multimodal Association Research Circulation Osseous (ARCO) classification was used for assessment of AVN. (2) Femoral neck fractures were assessed with the multimodal imaging approach. (3) Pre- and postoperative (=after sacrifice) alpha angles and femoral neck diameters were compared. RESULTS: (1) No signs for AVN according to the ARCO classification or (2) for femoral neck fractures were detected. (3) Mean alpha angles and femoral neck diameters decreased superiorly by at least 30° respectively 4 mm after the offset creation. CONCLUSIONS: Femoral osteochondroplasty can be performed effectively and without the risk of AVN or femoral neck fractures in ovine FAI.

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Femoral osteochondroplasty can be performed effectively without the risk of avascular necrosis or femoral neck fractures in an experimental ovine FAI model

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S U M M A R Y

Objective: The experimental induction of cam-type femoroacetabular impingement (FAI) in sheep is established. To tap the full potential of this ovine model, one should be able to perform a femoral osteochondroplasty safely. This study was based on previous cadaver experiments on the blood supply to the ovine femoral head and on the biomechanical strength of the proximal femur following offset creation. We hypothesized that offset creation in this ovine FAI model does not lead to (1) avascular necrosis (AVN) of the ovine femoral head or (2) iatrogenic femoral neck fractures and (3) can be performed effectively.

Design: In this experimental, controlled, prospective study nine sheep underwent unilateral FAI induction through an intertrochanteric, varus osteotomy. Seventy days following FAI induction, femoral osteochondroplasty was performed. Sheep were sacrificed after another 140 days. Radiographs, computed tomography (CT) scans and MRI were acquired. Histologic samples were stained with hematoxylin-eosin. (1) The multimodal Association Research Circulation Osseous (ARCO) classification was used for assessment of AVN. (2) Femoral neck fractures were assessed with the multimodal imaging approach. (3) Pre- and postoperative (=after sacrifice) alpha angles and femoral neck diameters were compared.

Results: (1) No signs for AVN according to the ARCO classification or (2) for femoral neck fractures were detected. (3) Mean alpha angles and femoral neck diameters decreased superiorly by at least 30° respectively 4 mm after the offset creation.

Conclusions: Femoral osteochondroplasty can be performed effectively and without the risk of AVN or femoral neck fractures in ovine FAI.

Introduction

In sheep, the femoral head-neck junction is aspherical by nature and resembles a cam-type deformity in human beings[1]. This eccentric configuration can be surgically reoriented by means of an extraarticular, closed-wedge, intertrochanteric, varus osteotomy for experimental induction of an inclusion-type (i.e., cam-type) of femoroacetabular impingement (FAI) (Fig. 1). Due to the quadrupedal gait in sheep, this conflict occurs at the posterior acetabulum during hip flexion. The induced conflict leads to macro- and microscopically verified chondro-labral lesions, analogous to the early findings in patients with FAI syndrome[1]. In this experimental ovine FAI model, the degenerative joint lesions progress over time and can be objectively described using biochemical magnetic resonance imaging (MRI) techniques[2].

We have previously established this animal model to provide a platform for experimental investigation of FAI[3]. This model

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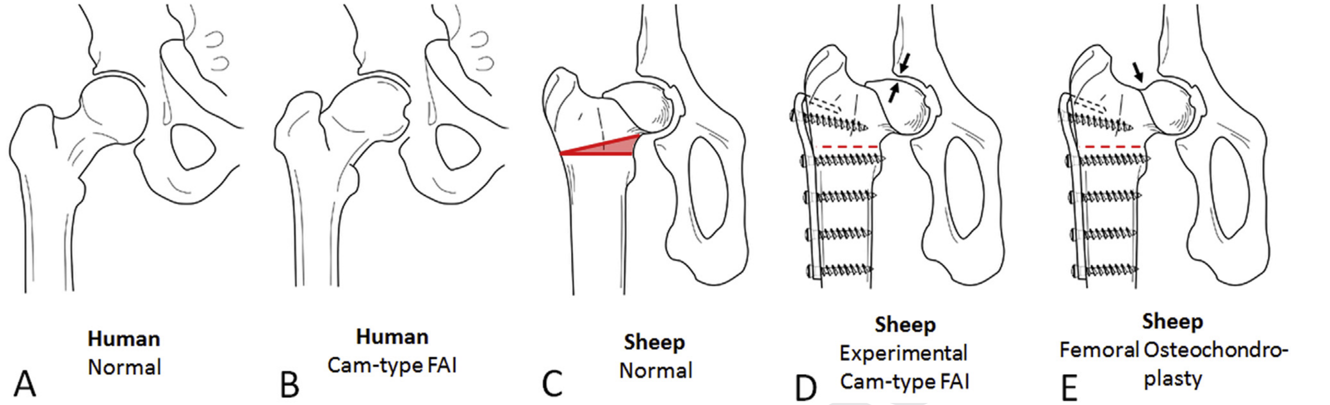

Fig. 1. (A) A normal human femoral head has a spherical shape. (B) In patients with a cam deformity the femoral head is aspherical. (C) Sheep have a natural superior asphericity. (D) With an extraarticular 15° closed wedge osteotomy of the proximal femur, an inclusion-type (cam-type) of FAI can be induced experimentally. (E) Femoral osteochondroplasty in this animal model would need to be performed in the superior aspherical portion – an area where the retinacular vessels are located in the human femur. The aim of this study was to assess whether such an offset creation in sheep can be performed effectively and without the risk of AVN and femoral neck fractures.

provides several distinct advantages compared to research on FAI in human beings. First, histology can be used as a gold standard to correlate with both radiographic evaluations of the normal and diseased joints, as well as to assess the effect of novel cartilage treatment options. Secondly, the surgical induction of FAI can be set at a given time point. This provides a standardized observation interval of the FAI syndrome and allows staged surgical correction to find the optimal time point for intervention. Finally, a prophylactic treatment can be performed with an objective assessment of the resulting joint damage. In addition, one of the key advantages of this model is the rapid induction of osteoarthritis. Early osteoarthritic changes occur within several months in sheep compared to several decades in human beings[4].

Although the model is well established, it is yet to be shown if a femoral osteochondroplasty can be performed safely[1,2] (Fig. 1). Preservation of the vascular blood supply to the ovine femoral head is necessary for a safe offset creation, i.e., establishing a spherical, concave femoral neck contour. The asphericity in sheep is located superiorly in an area where the retinacular vessels would enter the femoral epiphysis in human beings (Fig. 2)[5]. By contrast, we could show in a previous anatomical study that the ovine femoral head is supplied by anterior and posterior retinacular vessels[6]. The superior head-neck asphericity is free from vessels, theoretically allowing an offset creation in that area without the risk of avascular necrosis (AVN) of the ovine femoral head (Fig. 3). In addition, since sheep are unable to participate in partial weight bearing restrictions, it is unclear whether an offset creation can be performed without the risk of an iatrogenic femoral neck fracture. Our previous finite element analysis in cadaveric sheep demonstrated that an osteochondroplasty of up to 9 mm can be performed without substantially increasing the risk of femoral neck fractures during the normal sheep's activities of daily living[7].

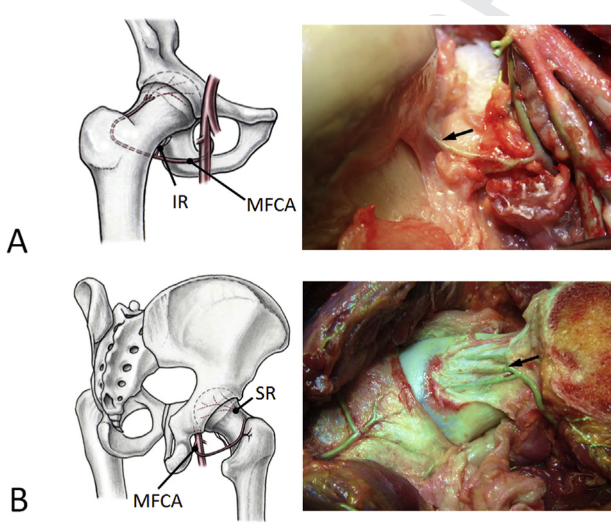

Fig. 2. (A and B) The blood supply to the human femoral head is shown with schematic drawings (left) and cadavers with injected coloured silicone (right). Two retinacular vessels from the medial femoral circumflex artery (MFCA) provide the blood supply to the epiphysis. (A) The inferior retinaculum (IR) runs within the Weitbrecht ligament (arrow). (B) The superior retinaculum (SR) (arrow) enters the femoral epiphysis superiorly at the cartilage bone junction (Courtesy M. Kalhor, M.D.; written permission pending).

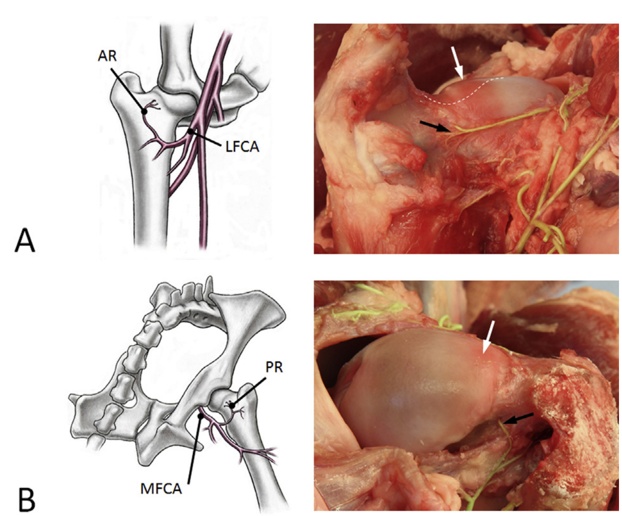

Fig. 3. (A and B) The blood supply to the ovine femoral head is shown with schematic drawings (left) and cadavers with injected coloured silicone (right). Similar to the human hip, two retinacular vessels provide the blood supply to the femoral head. By contrast, these vessels derive from different arteries: the medial and the lateral femoral circumflex artery (MCFA, LFCA). (A) The anterior retinaculum (AR) originates from the LFCA and enters the femoral epiphysis anteriorly (black arrow). (B) The posterior retinaculum (PR) originates from the MFCA and enters the femoral epiphysis posteriorly (black arrow). (A and B) The superior asphericity is free from vessels (white arrows) which should allow a safe osteochondroplasty (dotted line) in sheep.

The aim of this experimental, pilot study was to assess whether a femoral osteochondroplasty can be performed effectively and safely in this animal FAI model. We hypothesized that an offset creation does not lead to (1) AVN of the femoral head and (2) an iatrogenic femoral neck fracture and (3) can be performed effectively.

Methods

Experimental animals

We conducted an experimental, controlled, *in vivo* pilot study of ten female Swiss Alpine sheep (20 hips). This study was conducted according to Swiss laws for animal welfare and approved by the local governmental authorities (Kantonales Veterinäramt Zürich, Switzerland, No. 2/2014). Inclusion criterion was surgical induction of FAI via a standardized intertrochanteric, varus osteotomy. We had to exclude one sheep due to an accidental intracapital osteotomy. Each of the remaining 9 sheep (18 hips) underwent surgical induction of FAI on one side. The healthy contralateral side served as control. Mean age was 2.0 ± 0.5 years; (range, 1.5–2.5 years) corresponding to a mean age of approximately 22 human years (range, 17–28 years)[8,9]. The mean body weight was 60 ± 9 kg (range, 49–75 kg).

In eight sheep, a staged femoral osteochondroplasty was performed for FAI correction. One sheep underwent capsulotomy only without offset creation (sham surgery). The time interval between the first (FAI induction) and the second surgery (femoral osteochondroplasty) was 70 days, followed by an observation period of 140 days after osteochondroplasty until sacrifice resulting in total study period of 210 days.

Surgical procedure

Anesthesia was induced through a jugular catheter and was maintained with an intravenous constant-rate infusion of propofol plus a maximum 5% isoflurane (Minrad Inc., Buffalo, NY, USA) inhalation. Intravenous penicillin (35,000 IU/kg, Streuli Pharma, Uznach, Switzerland) and gentamycin (4 mg/kg, Vetagent, MSD Animal Health Care, Lucerne, Switzerland) and a subcutaneous injection of tetanus serum (3 ml, MSD Animal Health Care, Lucerne, Switzerland) were administered as preoperative antibiotic prophylaxis for 4 days. Epidural anesthesia was applied and analgesics were administered peri-/postoperatively for 3 days. Rocuronium (50 mg/ml, Rocuronium Fresenius, Fresesnius Kabi, Oberdorf, Switzerland) was used as a nondepolarizing muscle relaxant.

For induction of FAI, sheep were placed in the lateral decubitus position on the contralateral side[1,2]. A slightly curved 15–20 cm incision was made on the lateral aspect of the thigh over the palpable interval between the vastus lateralis and the gluteobiceps muscles (corresponding to the Gibson interval in human beings). The gluteobiceps muscle in sheep corresponds to a fused gluteus maximus and biceps femoris muscle in human beings. A standard subvastus approach was performed with elevation of the vastus lateralis- and intermedius muscles (Fig. 4). A 15° medially-based wedge was cut just above the lesser trochanter using a special cutting jig. Accurate rotational alignment was achieved using the linea aspera as anatomic reference. A slightly contoured 3.5 mm double hook plate originally designed for dogs (DePuy Synthes, Warsaw, IN, USA, formerly Synthes) was used. Compression was achieved with eccentric drilling of the screws. The fascia of the vastus lateralis muscle was then reapproximated to the lateral intermuscular septum and the wound closed in layers. During recovery, animals were kept in a suspension system for 4 weeks. This sling basically allows full weight bearing but prevents animals from lying down and getting up. Subsequently, the sheep were kept in small three-sheep pens for 2 weeks and were permitted to roam freely 6 weeks postoperatively (supplementary electronic material for video documentation).

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.joca.2017.10.009.

At day 70, all sheep underwent a second surgery. Using the same incision, we used two different surgical approaches to expose the lateral asphericity: five sheep with a gluteus split approach and four with an anterior approach. For the gluteus split approach, the gluteus medius muscle was split and the underlying gluteus minimus muscle retracted distally for exposure of the joint capsule [Fig. 5(A)]. For the intermuscular anterior approach, the interval between the gluteus medius and minimus muscle was entered for exposure of the joint capsule [Fig. 5(B)]. Both approaches enabled a direct visualization of the course of the anterior and posterior retinacular vessels. However the anterior, posterior retinacular vessels could be potentially injured depending on the surgical approach. The decision to perform two different approaches was based on the lack of information prior to this study regarding the safety of either approach *in vivo*. Choice of surgical approaches was made in an alternating fashion: The first sheep underwent offset creation by means of a gluteus split approach, followed by an anterior approach for the next sheep and so on.

After an H-shaped capsulotomy, the femoral osteochondroplasty was performed in a standard way using curved chisels and a high-speed burr (Air Pen Drive, DePuy Synthes, Warsaw, IN,

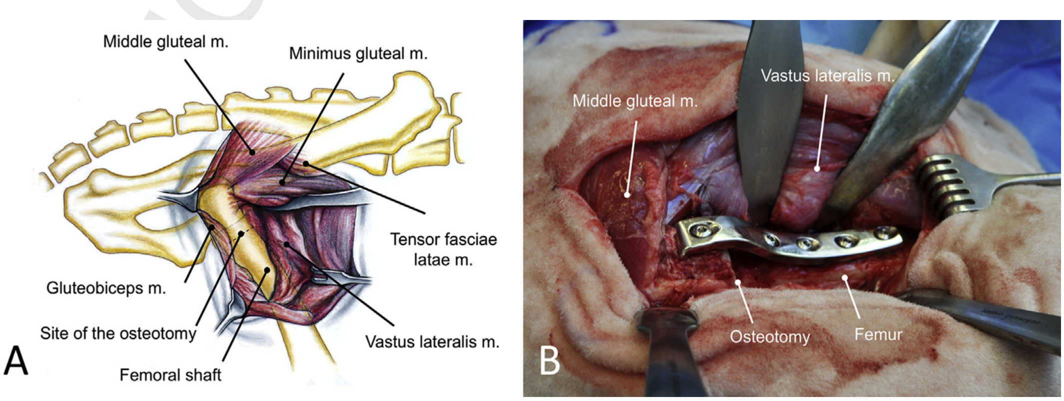

Fig. 4. (A and B) The surgical approach to the ovine femur is shown. The femur is exposed by retraction of the gluteobiceps muscle (fused biceps femoris and gluteus maximus muscles in sheep) posteriorly and elevation of the vastus lateralis muscle anteriorly. (B) Intraoperative image after fixation of the osteotomy.

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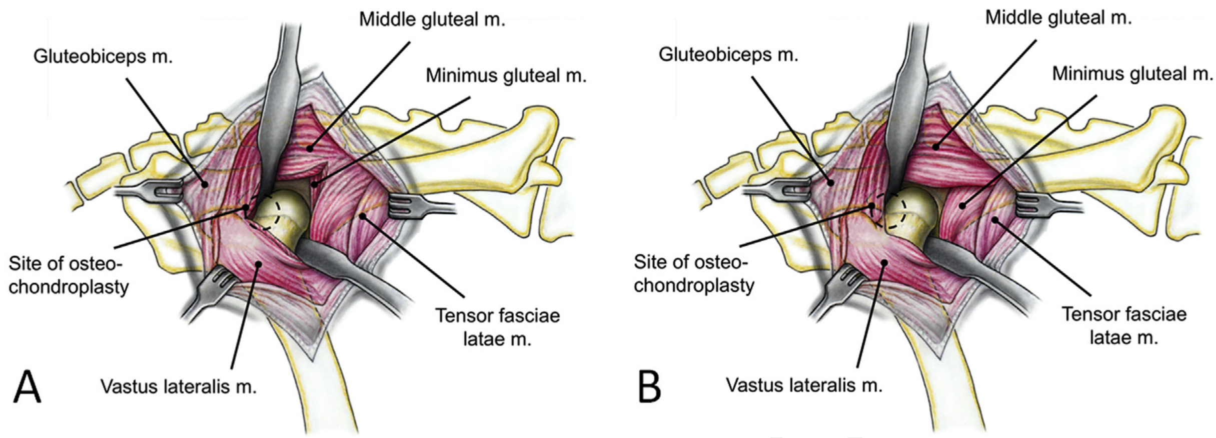

Fig. 5. (A and B) Two different surgical approaches were used to expose the superior asphericity. Either a gluteus split approach or an anterior approach was used. Choice of either surgical approach was randomly made. (A) The gluteus split approach divides the muscle belly of the middle gluteal muscle with preservation of the tendinous attachment to the greater trochanter. The minimus gluteal muscle is retracted inferiorly. (B) In the intermuscular anterior approach, the middle gluteal muscle is retracted superiorly and the minimus gluteal muscle is retracted inferiorly.

USA, formerly Synthes). Intraoperatively, the offset correction was performed until an impingement-free range of motion was established, in particular during flexion/extension.

In one sheep with a gluteus split approach, we performed a capsulotomy only without offset creation (sham surgery). The same postoperative protocol was applied following the second surgery except for the fact that sheep were kept in the suspension device for only 2 weeks. Sheep were sacrificed after a total of 210 days.

Diagnostic imaging acquisition

Before the first and the second surgery, as well as after sacrifice, anteroposterior (AP) and axial radiographs of the pelvis and computed tomography (CT) scans were acquired. Sheep were euthanized via an intravenous injection of 30–40 ml Pentobarbital (300 mg/ml; Esconarkon, Streuli Pharma AG, Uznach, Switzerland) through a jugular catheter. After sacrifice, the hardware was removed and MRI performed.

AP pelvis radiographs were acquired directly before or after the surgery with the sheep under anesthesia. Sheep were in supine position with maximal flexion of the hip. This perpendicular projection enables an orthogonal assessment of the superior asphericity. The axial view was acquired with both hips in neutral position for visualization of the typically spherical anterior head-neck junction.

CT was performed with 1.5 mm slice thickness (Somatom Sensation Open, Siemens Medical Solutions, Erlangen, Germany). The scanned volume included the entire pelvis and femur and the following parameters: voltage 120 kVp; intensity 300 mAs; pitch 0.65; field of view 50 cm; voxel size 1 mm[3], reconstruction kernels B20 and B60.

For the MRI, all sheep received gadodiamide intravenously (0.2 mmol/kg Omniscan, GE Healthcare, Opfikon, Switzerland). In order to improve image quality, the hip joint with the adjacent muscles including the entire hemipelvis and femur was prepared to fit in the coil. MRI was performed at 3 T (Ingenia, Philipps, Medical Systems AG, Zürich, Switzerland) using a 16 channel transmit-receive knee coil (Philipps, Medical Systems AG, Zürich, Switzerland). In both operated and control hips, we acquired a 2D radial proton density-weighted (PD) turbo spin-echo (TSE) sequence without fat suppression (Repetition-time [TR]/echo-time [TE]: 3085/30 ms, flip angle 90°, matrix 304 × 299, field of view 7 cm, bandwidth 198.6 Hz/Px, acquisition time 9:25 min, 30 slices); a 2D radial T2-weighted TSE sequence without fat suppression (Repetition-time/echo-time: 2000/13 ms, flip angle 90°, matrix 240 × 194, field of view 10 cm, bandwidth 291 Hz/Px, acquisition time 16:32 min, 30 slices). For acquisition of radial images the centre of the ovine femoral neck was used as axis of rotation, similar to the planning of radial slices for clinical magnetic resonance (MR) imaging in FAI[10].

Harvesting and processing of histological samples

After MR imaging, the hip was disarticulated and inspected macroscopically. Three bone-cartilage samples (1.5 × 3.5 cm) were acquired from the femur. Femoral samples included a central, horizontal cut through the fovea capitis in line with the tip of the greater trochanter. Perpendicular to that, anterior and posterior cuts were made vertically through the femoral head to obtain representative samples for histological analysis (Supplementary Fig. 1). Samples were fixed in 4% paraformaldehyde for 14 days. After a three-times washout with an ascending alcohol series samples were kept in xylene for 4 days for degreasing. Samples were then embedded in methylmetacrylate and 300 μm thick section prepared and stained with toluidine blue and haematoxylin-eosin.

Evaluation

For hypothesis 1, the presence of AVN was assessed according to internationally established criteria from the Association Research Circulation Osseous (ARCO) from 1994[11,12]. These criteria describe a stage-dependent multimodal classification using histology, conventional radiographs, CT and MRI. AVN was defined at its earliest stage which is ARCO O (=positive histologic diagnose of AVN, and negative diagnose of AVN on macroscopic inspection/radiographs/CT/MRI) (Table I). Prior to evaluation, all tissue samples and images were blinded. Macroscopic lesions were visually inspected according to standard criteria (Table I) by an orthopaedic surgeon (MT) with extensive experience in joint-preserving hip surgery. One musculoskeletal pathologist (HED) evaluated all histological samples dichotomously using previously described criteria (Table I)[13,14]. Radiographs, CT- and MRI scans were assessed in consensus using the criteria mentioned in Table I.

For hypothesis 2, radiographs and CT scans were assessed for irregular, radiolucent or radiopaque fracture lines in the femoral

Table I
The modified criteria for staging of AVN of the femoral head according to the ARCO from 1994[9]

Stage	Histology[13,14]	Macroscopy[11,12]	Conventional radiographs	CT	MRI[9,10]
0	Dead thickened bone trabeculae, empty osteocytic lacunae, shrunken pyknotic osteocytes, bone marrow tissue necrosis	Negative	Negative	Negative	Negative
I		Opaque yellowish discoloration of bone marrow	Negative	Negative	Hypointense band-like lesion surrounding the necrotic area
II		Sclerotic margin with surrounding whitish reparative tissue	Subtle signs of osteosclerosis, focal osteoporosis or cystic changes		Demarcation of necrotic bone: hyperintense inner line, hypointense outer line (double-line sign)
III (Early)		Subchondral fracture just beneath the cartilage, no collapse	Early subchondral fracture: irregular radiolucent/-paque line (crescent sign), no collapse		Subchondral fracture: hypo/hyperintense line parallel to articular surface, no collapse
III (Late)		Subchondral fracture just beneath the cartilage, collapse	Subchondral fracture: irregular radiolucent/-paque line (crescent sign), collapse		Subchondral fracture: hypo/hyperintense line parallel to articular surface, collapse
IV	Secondary osteoarthritis				

neck with or without displacement of the femoral head. The MRI criterion for a femoral neck fracture, was a hypointense sclerotic line, with or without displacement of the femoral head. Imaging evaluation was performed in consensus by two readers with 4 years (FS) and 15 years (MT) of experience in musculoskeletal imaging of the hip.

For hypothesis 3, CT scans which were acquired preoperatively (before FAI induction [=first surgery] and femoral osteochondroplasty [=second surgery]) and after the sacrifice (after FAI induction [=first surgery] and femoral osteochondroplasty [=second surgery]) were radially reformatted. Twelve radial images around the femoral neck axis[10] were used for circumferential measurements at each 'half-hour' position of the joint. The most prominent appearance of the greater trochanter served as landmark for the 12 o'clock position of the femur[10]. Two quantitative parameters were assessed: the alpha angle[15] and the resection depth[7] (Fig. 6). Pre- and postoperative alpha angles were measured at two different timepoints to assess the efficacy of the offset correction. The resection depth was calculated as the difference between the pre- and postoperative femoral neck diameters. To assess interobserver reproducibility and intraobserver reliability two observers measured alpha angles and femoral neck diameters at two different time points on a random sample of 30 radially reformatted CT images. Intraclass correlation coefficient (ICC) was used for comparison. Interobserver reproducibility was 0.959 (95% confidence interval [CI], 0.897–0.984) for alpha angles and 0.980 (95% CI, 0.932–0.994) for femoral neck diameters. Intraobserver reliability of observer 1 was 0.936 (95% CI, 0.842–0.975) for alpha angles and 0.984 (95% CI, 0.945–0.995) for femoral neck diameters. Intraobserver reliability of observer 2 was 0.919 (95% CI, 0.801–0.968) for alpha angles and 0.965 (95% CI, 0.884–0.990) for femoral neck diameters.

Descriptive statistics (mean, standard deviation, range) were calculated. Pre- and postoperative measurements were grouped hourly. Due to the small sample size, the non-parametric Wilcoxon rank-sum test was used for comparison of pre- and postoperative alpha angles and femoral neck diameters. A p-value < 0.05 indicated statistical significance. We used WinSTAT (R.Fitch Software, Bad Krozingen, Germany) for Microsoft Excel 2016 (Microsoft Corporation, Redmond, USA). Intraclass correlation coefficient was used for assessment of interobserver reproducibility and intraobserver reliability[16].

Results

There was no necrosis (0/8; 0%) in any of the ovine femoral heads that had undergone surgical induction of FAI and staged femoral osteochondroplasty (Supplementary Fig. 2). More specifically with respect to the ARCO classification, we did not find signs of AVN in the most sensitive modalities, namely histology and MRI (Fig. 7). Similarly, there was no necrosis (0/9; 0%) in the contralateral healthy hip joints nor in the hip undergoing the sham procedure (0/1; 0%) (Fig. 8).

There was no iatrogenic femoral neck fracture in any of the ovine femurs that had undergone surgical induction of FAI and staged femoral osteochondroplasty (0/8; 0%) as assessed with radiography (Supplementary Fig. 2) and CT, macroscopic inspection, MRI or histology (Fig. 7). Similarly, there was no iatrogenic femoral neck fracture in the contralateral healthy hip joints (0/9; 0%) nor in the hip undergoing the sham procedure (0/1; 0%) (Fig. 8).

Mean alpha angles decreased at least by 30° from preoperatively to postoperatively at the 11–1:30 o'clock position after the femoral osteochondroplasty (e.g., 12–12:30 o'clock: mean $85 \pm 5°$ vs $55 \pm 9°$, $p < 0.001$, Table II). Mean femoral neck diameter decreased at least by 4 mm from pre-to postoperatively at the 11–1:30 o'clock position after femoral osteochondroplasty (e.g., 12–12:30 o'clock: mean 24 ± 1 mm vs 20 ± 3 mm, $p < 0.001$, Table III).

Discussion

There has been a tremendous gain of knowledge in the field of FAI since its first description in 2003[17,18]. However, there remain several important questions that cannot be answered using standard clinical research practices. For example, the histological evaluation of potential cartilage therapies would require second look surgeries for harvesting representative tissue samples. Moreover, a comparative analysis between promising biochemical MRI techniques or serum biomarkers and the histological gold standard in different stages of early osteoarthritis is not possible[19–21]. Recruiting patients for randomized, controlled, prospective studies to determine the optimal time point of correction can be problematic given the reproducible success of surgical treatment for FAI[22–27]. Translational medicine can be helpful to answer such clinically important questions. The prerequisite of such an approach is the reproducible induction of FAI and the safety of the surgical therapy. While the experimental induction of cam-type FAI in sheep is established, the feasibility of femoral osteochondroplasty is yet to be shown[1]. The aim of this study was to investigate if offset creation in sheep can be performed effectively without the risk of AVN or iatrogenic femoral neck fracture.

We could show that an osteochondroplasty of the superior asphericity can be performed effectively without the risk of AVN in this experimental FAI model. Based on our previous anatomical dissections in sheep, the osteochondroplasty was performed under

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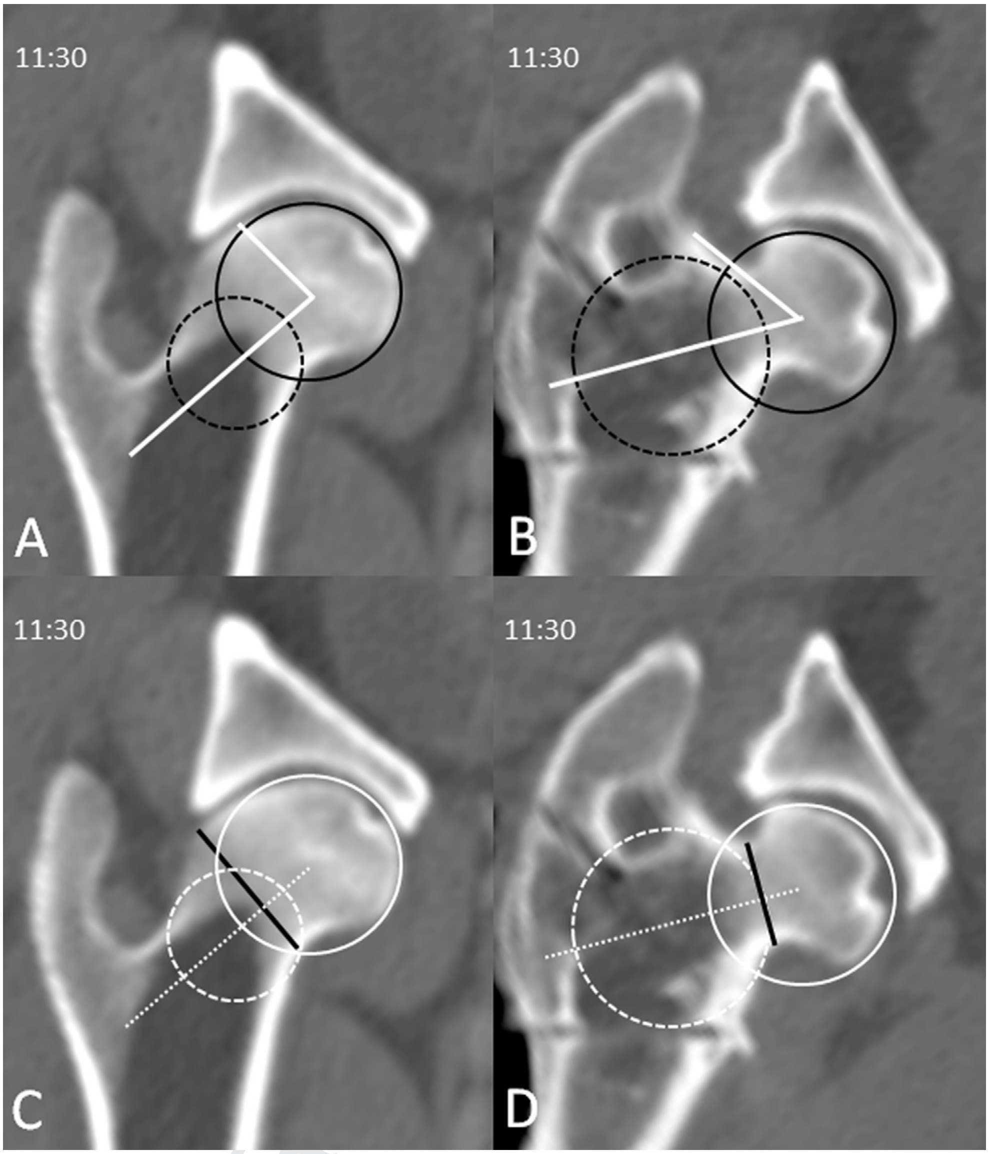

Fig. 6. (A, C) Pre- and (B, D) postoperative (at sacrifice = after FAI induction and offset creation) radially reformatted CT images from the same sheep at the 11:30 o'clock position. (A, B) Alpha angle measurement: The proximal femoral neck axis (white line) was defined with two best fitting circles over the femoral head and the femoral neck (black circles). The alpha angle spans between a line which connects the femoral head center with the beginning of the asphericity and the femoral neck axis. Alpha angle decreased from 88° preoperatively to 56° postoperatively after offset creation. (C, D) Measurement of femoral neck diameter: The proximal femoral neck axis (white dashed line) was defined with two best fitting circles over the femoral head and the femoral neck (white circles). The femoral neck diameter (black line) was measured perpendicular to the femoral neck axis at the smallest diameter of the femoral head-neck junction. Femoral neck diameter decreased from (C) 23 mm preoperatively to (D) 17 mm postoperatively.

direct visualization of the anterior and posterior retinacular vessels and care was taken to avoid their laceration[6]. In contrast to humans (Fig. 2), the superior portion of the femoral head is free from vessels in sheep (Fig. 3)[5,6]. One can ask if the observation time of 140 days after femoral osteochondroplasty is long enough to establish a necrotic femoral head. Previous experimental inductions of AVN by surgical vascular deprivation in other species showed evidence of femoral head collapse typically within the first 8 weeks[28]. More specifically, an experimental AVN model in sheep was introduced recently, in which induction of AVN was achieved through ligation of the vascular supply of the femoral head and placement of a cryoprobe into the femoral head. With this approach, histologic- and MR signs of AVN such as geographic lesions with a sclerotic margin, double line signs, femoral head collapse and joint incongruence were detectable between 6 and 12 weeks[29].

Since the ambulation time between the cam decompression and the sacrifice in our study was almost twice as long (20 weeks, 140 days), it is unlikely that we would have missed any cases of AVN. With our multimodal imaging approach combined with the histologic gold standard, even early stages of AVN would have been detected.

We did not observe femoral neck fractures in our animal model, neither in the hips undergoing FAI induction and femoral osteochondroplasty (Fig. 7) nor in the control hips (Fig. 8). This is important for several reasons. Reportedly, more than half of the iatrogenic fractures after osteochondroplasty in human FAI are caused by violation of weight-bearing precautions[30]. Sheep are inherently fully weight-bearing after both intertrochanteric osteotomy and osteochondroplasty, despite the use of the described suspension device. Under laboratory conditions, we

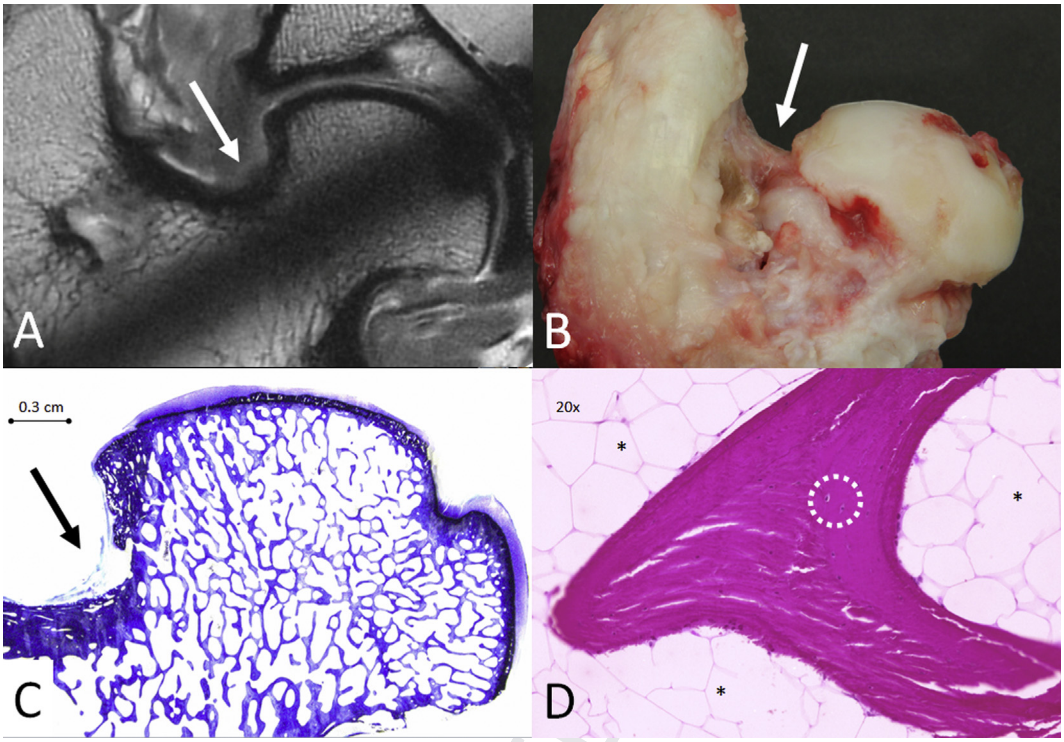

Fig. 7. (A–D) Post-mortem MRI-, macroscopic-, and histologic evaluation of the same sheep shows no AVN or femoral neck fractures after staged femoral osteochondroplasty. (A) Radial proton density-weighted TSE image shows a spherical, superior femoral head-neck junction (arrow) with intact cortical bone and normal fat marrow signal. (B) Cadaveric femur and (C) toluidine blue staining show intact cortical bone and improved femoral offset (arrows). (D) Hematoxylin-eosin staining (20× magnification) shows normal osteocytic lacunae (circle) and no bone marrow tissue necrosis (asterisk).

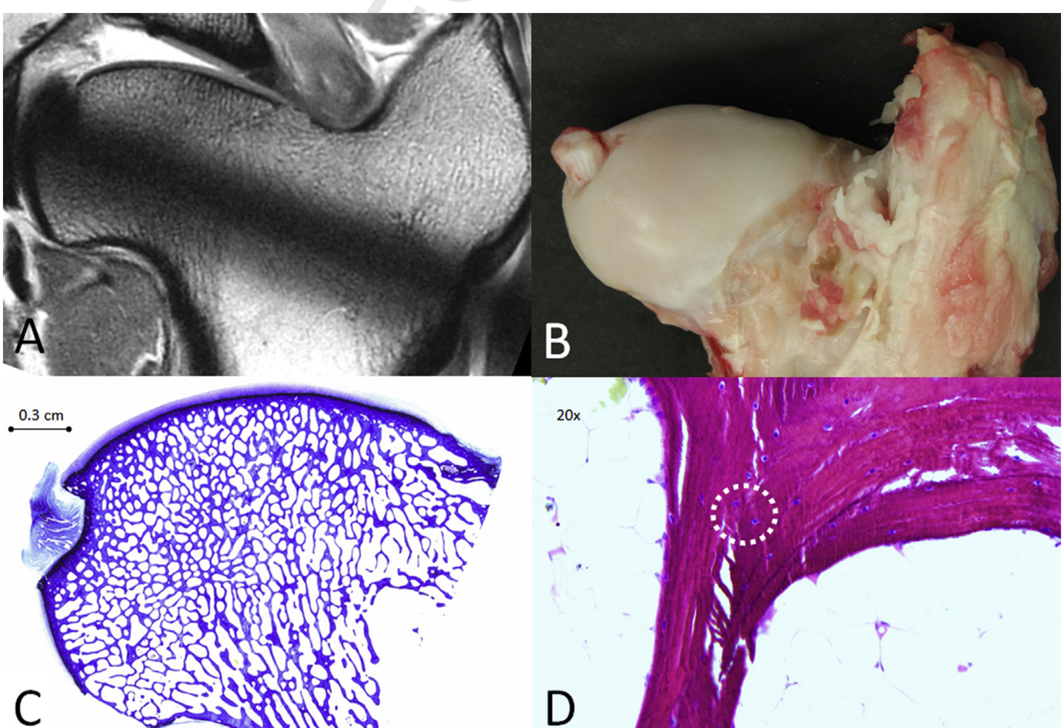

Fig. 8. (A–D) Post-mortem MRI-, macroscopic- and histologic evaluation of the same sheep shows no AVN or femoral neck fractures in a healthy contralateral, control hip. (A) Radial proton density-weighted TSE image shows intact cortical bone and normal fat marrow signal. (B) Fresh cadaveric femur and (C) toluidine blue shows intact cortical bone and normal osseus architecture. (D) Hematoxylin-eosin staining (20× magnification) shows normal osteocytic lacunae (circle) and no bone marrow tissue necrosis (asterisk).

Table II
Comparison of alpha angles measured on radially reformatted CT scans preoperatively (before FAI induction and femoral osteochondroplasty) vs postoperatively (after sacrifice = after FAI induction and femoral osteochondroplasty)

Parameter	Time (Clockface position)									
	11–11:30	12–12:30	1–1:30	2–2:30	3–3:30	4–4:30	7–7:30	8–8:30	9–9:30	10–10:30
Preoperative alpha angle (°)	84 ± 10 (57–96)	85 ± 5 (78–97)	83 ± 10 (58–98)	51 ± 9 (36–71)	39 ± 3 (34–46)	39 ± 3 (35–44)	57 ± 6 (45–67)	52 ± 7 (40–62)	43 ± 4 (38–52)	43 ± 5 (34–53)
Postoperative alpha angle (°)	53 ± 7 (40–63)	55 ± 9 (37–67)	53 ± 8 (42–72)	49 ± 5 (40–58)	42 ± 4 (35–49)	43 ± 5 (34–52)	52 ± 7 (35–60)	51 ± 6 (40–58)	44 ± 5 (33–54)	46 ± 5 (37–55)
p-Value	<0.001	<0.001	<0.001	0.932	0.002	0.008	0.004	0.551	0.422	0.017
Mean decrease in alpha angles (°)	31 ± 11 (0–48)	30 ± 10 (18–48)	30 ± 15 (6–51)	2 ± 10 (-9–22)	−3 ± 3 (-11–0)	−4 ± 4 (-12–3)	5 ± 6 (-3–15)	0 ± 5 (-9–10)	0 ± 5 (-7–13)	−3 ± 5 (-11–6)

Continuous values are given as mean ± standard deviation with range in parenthesis.

could show that even with an extended offset creation in sheep, the femur could still support more than 4.5 times of the upmost force involved during walking. In this cadaver model, however, we examined the strength of the native ovine femur without previous femoral osteotomy[7]. Thus, previously, we were unable to predict whether an offset correction could be done safely *in vivo*. Nevertheless, despite the wide intra- and inter-individual variability of hip joint in loading forces of the ovine hip[31], our findings confirm the results of our previously performed cadaveric finite element analysis.

One possible reason for not having observed AVN or iatrogenic femoral neck fractures in the current study would be a highly insufficient offset creation. The described surgical technique enables a direct visualization of the retinacular vessels and dynamic intraoperative range of motion testing. Alpha angles and resection depths were compared circumferentially to assess the efficacy of the offset creation in detail. A mean reduction of at least 30° in alpha angles and a minimum 4 mm increase in femoral head-neck offset was achieved between the 11–1 30 o'clock position (see Tables II and III). This is comparable to human beings and corresponds to an effective femoral osteochondroplasty[33,34]. Between the 11–1:30 o'clock position, the highest mean postoperative alpha angle following femoral osteochondroplasty was 55 ± 9°. By contrast, preoperative alpha angles of the anterior/posterior circumference, where no bone was resected were within normal ranges (maximum mean alpha angle: 2–2:30 o'clock; 49 ± 5°) and showed only minor, if any changes after femoral osteochondroplasty[15]. Maximum superior resection depth was 9 mm in one hip. Regardless, no bone necrosis or iatrogenic femoral neck fracture occurred. This confirms the results of a previous study, in which offset creation of 9 mm in a cadaveric ovine femur did not substantially alter the mechanical integrity of the femur[7].

This study has several limitations. First, the sample size is relatively small. However, if there had been a conceptual error of our model, we would have observed AVN in the majority, if not all our animals. This was not the case even in the histological evaluation. A second limitation is the surgical learning curve related to the surgical approaches. However, the orthopaedic surgeon who performed the osteochondroplasties in the sheep model is an experienced orthopaedic surgeon with more than 10 years of expertise in both open and arthroscopic joint preserving hip surgery. This facilitates a proper identification and protection of the retinacular vessels intraoperatively even if they are not in the same location as in human beings. In addition, the approaches and the offset creation were tested ahead of this study in the cadaver lab. This can reportedly lower the risk of technical problems such as over- and undercorrection or relevant surgical complications[35]. Third, we did not analyze the entire femoral head histologically but instead assessed the most representative areas of the femur. This included the anterior and posterior part of the hemisphere where the retinacular vessels enter the femoral head and a central section through the femoral head which represents the watershed zone of the vascular supply (Supplementary Fig. 1). The femoral ostoechondroplasty was performed superiorly, thus this area would theoretically be at the greatest risk of developing AVN. The evaluation of the viability of the remaining femoral head was done based on MRI which showed no evidence of AVN (Fig. 7). Fourth, due to the limited sample size, we performed sham surgery in one sheep only. Fifth, choice of surgical approaches was not randomized.

In conclusion, this study could show that femoral osteochondroplasty can be performed without the risk of AVN or femoral neck fractures in an experimental ovine FAI model. This opens the door to investigate the value of potential prophylactic treatment and to analyze the effect of surgical treatment on cartilage degeneration.

Table III
Comparison of femoral neck diameter measured on radially reformatted CT scans preoperatively (before FAI induction and femoral osteochondroplasty) vs postoperatively (after sacrifice = after FAI induction and femoral osteochondroplasty)

Parameter	Time (Clockface position)					
	11–11:30	12–12:30	1–1:30	2–2:30	3–3:30	4–4:30
Preoperative femoral neck diameter (mm)	22 ± 3 (16–27)	24 ± 1 (22–27)	24 ± 1 (22–27)	22 ± 2 (17–24)	18 ± 1 (16–20)	18 ± 1 (16–20)
Postoperative femoral neck diameter (mm)	18 ± 3 (11–24)	20 ± 3 (16–24)	20 ± 3 (15–24)	21 ± 2 (16–24)	18 ± 1 (16–20)	17 ± 1 (15–20)
P-Value	<0.001	<0.001	<0.001	0.017	0.103	0.215
Resection depth (mm)	4 ± 3 (1–6)	5 ± 1 (2–8)	5 ± 1 (0–9)	1 ± 2 (-1–7)	0 ± 1 (-1–3)	0 ± 1 (-1–1)

Continuous values are given as mean ± standard deviation with range in parenthesis.

Author contributions

FS: technical support for data acquisition, image data collection, analysis and interpretation of data, initial draft, manuscript editing, final approval of the version to be submitted, ensures the integrity of the work.

LA: administrative, technical and logistic support for data acquisition, collection and assembly of data, initial draft, final approval of the version to be submitted.

TL: technical support for data acquisition, initial draft, manuscript editing, final approval of the version to be submitted.

SDS: technical support for data acquisition, manuscript editing, final approval of the version to be submitted.

KN: administrative, technical and logistic support for data acquisition, collection and assembly of data, manuscript editing, final approval of the version to be submitted.

NW: administrative, technical and logistic support for data acquisition, collection and assembly of data, initial draft, final approval of the version to be submitted.

HED: analysis and interpretation of data, manuscript editing, final approval of the version to be submitted.

BvR: administrative, technical and logistic support for data acquisition, manuscript editing, final approval of the version to be submitted, ensures the integrity of the work.

PRK: administrative, technical and logistic support for data acquisition, manuscript editing, final approval of the version to be submitted.

MT: concept and design of the study, manuscript editing, final approval of the version to be submitted, ensures the integrity of the work.

Conflict of interest

No author has a commercial association that might pose a conflict of interest in connection with the submitted article.

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Supplementary data

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Uncited reference

32.

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